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Homogeneous Boiling Explosion Condition: From an Energy Point of View

Mohammad Nasim Hasan[a]* Ashik Hasan[a], Suhaimi Ilias[b], Yuichi Mitsutake[b], Masanori Monde[b]

[a]Department of Mechanical Engineering, Bangladesh University of Engineering & Technology, Dhaka-1000, Bangladesh
[b]Department of Mechanical Engineering, Saga University, Saga, 840-8502, Japan

Abstract

When a liquid homogeneously boils explosively during non-equilibrium heating is very important as the characteristics of the system before and after the occurrence of homogeneous boiling explosion is significantly different. In the present study, we studied homogeneous boiling explosion condition from an energy point of view: how much energy is required to boil the liquid explosively by homogeneous nucleation from a given initial temperature under any heating conditions. As a representative one, water heating at atmospheric pressure has been considered under three different heating conditions namely; i) linear heating at the boundary ii) high heat flux pulse heating and iii) liquid contact upon high temperature surface. The analytical formulations for cumulative energy distribution in the liquid under various liquid heating conditions have been derived and the cumulative energy density within the liquid are calculated. It has been found that the instantaneous cumulative energy density very near to the liquid boundary is several times higher than that corresponding to the thermal penetration depth for all liquid heating cases. The present study shows that, the cumulative energy density at the boiling explosion over a characteristic liquid cluster being equal to the size of a critical embryo is independent of the heating parameter for any of the liquid heating cases and for a given initial condition, it has been found to be almost constant for all liquid heating conditions. However, the cumulative energy density at the boiling explosion depends on the liquid initial temperature. The obtained results are compared with other numerical results reported in the literature for water subjected to uniform volumetric heating at atmospheric pressure.

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Keywords: Homogeneous boiling; Boiling explosion, Cumulative energy density

* Corresponding author. Tel.: +880-1921506445; fax: +880-02-9665636.
*E-mail address:*nasim@me.buet.ac.bd

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1. Introduction

Phase transformation phenomenon is very common in thermal systems. According to the classical thermodynamics, a liquid boils when its temperature becomes equal to the saturation temperature at the prevailing pressure. However, in some particular cases when the system is prevented from external disturbances through no contamination, smooth surface contact, no physical disturbance etc., the boiling temperature of a pure substance may exceed the thermodynamic saturation temperature. Such a liquid is known as metastable superheated liquid. Depending on the liquid superheat, the liquid boils explosively and eventually returns to the state of equilibrium. The study of metastable liquid and the associated boiling explosion has found application in some safety problems in industry. Recent development in bubble actuated micro-electronic-mechanical systems such as micro-pump, micro-injector etc. has uncovered a very potential field of superheat induced micro bubble explosions.

Nomenclature

b	boundary heating rate (K/s)	T_i	solid-liquid interface temperature (°C)
E	cumulative energy deposited in the liquid (J/m^2)	r_c	radius of critical vapor embryo (m)
$\dot{E}^*$	cumulative energy density in the liquid (J/m^3)	x_e	liquid cluster size (m)
m	relative energy density factor		
q_w	boundary heat flux (W/m^2)	Greek	symbol
t	Time (s)	α	thermal diffusivity
t^*	time of boiling explosion (s)	β	thermal inertia ratio of solid and liquid
T	Temperature (°C)	δ_{th}	thermal penetration depth
T_0	liquid initial temperature (°C)	χ	thermal conductivity
T_{avg}	average temperature in the liquid cluster (°C)	η	modified Fourier number
T^*_{avg}	maximum cluster temperature		

Many experimental studies [1-3] have been conducted for the understanding of heat and mass transfer processes in a pure liquid subject to intense heating. These studies focused much on the incipience of bubble generation, the mechanism of boiling nucleation and the effect of rapid oscillation of bubble growth and collapse on the liquid flow pattern under various liquid heating conditions. Incidentally, the authors developed a theoretical model [4] to predict the boiling explosion condition and obtained the model predicted time and temperature at the boiling explosion to be in good agreement with the experimental observations under various liquid heating conditions. In the present study we focused on the homogeneous boiling explosion condition from an energy point of view that is how much energy is necessary to induce homogeneous boiling explosion for a given initial condition irrespective of liquid heating process and how this energy is related to the heating parameter. As a representative one, water heating at atmospheric pressure with various liquid initial temperatures has been considered.

2. Prediction of Homogeneous Boiling Explosion Condition in Water

To determine the time and temperature at which homogeneous boiling explosion occurs in water during heating under various heating conditions, the mechanistic model proposed by the authors [4] has been used. In this model, a particular stage of liquid heating (t^*) is defined as the homogeneous nucleation boiling explosion at which bubble generation and growth due to homogeneous nucleation inside a characteristic liquid cluster, x_e, causes the average cluster temperature, T_{avg}, to decrease namely, $dT_{avg}/dt \leq 0$. The summary of homogeneous boiling explosion characteristics i.e. t^*, T^*_{avg} and x_e [5-6] are mentioned in Tables 1, 2, and 3 for water (20 °C) heating with linear boundary condition ($T = bt$; $10 < b < 10^9$ K/s), high heat flux boundary condition ($q = q_w$; $15 < q_w < 1000$ MW/m^2) and liquid heating upon contact with hot surface i.e. constant temperature boundary condition ($T = T_i$; $303 < T_i < 307$ °C) respectively. As mentioned in these Tables, the time and temperature at the boiling explosion change with the heating parameter especially the variation in time is very drastic. However, for a given liquid initial condition, the boiling explosion condition should refer a unique state irrespective of liquid heating condition. The present study is aimed to find out a unique a criterion for homogeneous boiling explosion from an energy point of view. The concept and necessary formulations are described in the next.

Table 1: Homogeneous nucleation boiling characteristics during linear boundary heating of water (20 °C) [5]

b (K/s)	**x_e (nm)**	**T^*_{avg} (°C)**	**t^* (s)**	$\dot{E}^*(\delta^*_{th})$ **(J/m^3)**	$\dot{E}^*(\eta^*)$ **(J/m^3)**
10	6.72	301.8	2.82×10^{1}	1.85×10^{8}	1.18×10^{9}
10^3	6.32	303.9	2.84×10^{-1}	1.86×10^{8}	1.19×10^{9}
10^5	5.88	306.3	2.87×10^{-3}	1.88×10^{8}	1.20×10^{9}
10^7	5.38	309.2	2.90×10^{-5}	1.90×10^{8}	1.21×10^{9}
10^9	4.79	312.8	2.97×10^{-7}	1.94×10^{8}	1.22×10^{9}

Table 2: Homogeneous nucleation characteristics during high heat flux (q) pulse heating of water (20°C) [6]

q_w (W/m^2)	**x_e (nm)**	**T^*_{avg} (°C)**	**t^* (s)**	$\dot{E}^*(\delta^*_{th})$ **(J/m^3)**	$\dot{E}^*(\eta^*)$ **(J/m^3)**
15×10^6	5.81	306.7	7.23×10^{-4}	2.05×10^{8}	1.20×10^{9}
100×10^6	5.39	309.1	16.547×10^{-6}	2.07×10^{8}	1.21×10^{9}
250×10^6	5.17	310.4	2.684×10^{-6}	2.08×10^{8}	1.22×10^{9}
500×10^6	5.00	311.5	6.808×10^{-7}	2.10×10^{8}	1.22×10^{9}
750×10^6	4.89	312.2	3.0601×10^{-7}	2.11×10^{8}	1.23×10^{9}
1000×10^6	4.81	312.7	1.7386×10^{-7}	2.12×10^{8}	1.23×10^{9}

Table 3: Homogeneous nucleation boiling characteristics during water (20 °C) contact with hot carbon steel surface (β = 8.81) [5]

T_b (°C)	**T_i (°C)**	**x_e (nm)**	**T^*_{avg} (°C)**	**t^* (s)**	$\dot{E}^*(\delta^*_{th})$ **(J/m^3)**	$\dot{E}^*(\eta^*)$ **(J/m^3)**
336	303.9	6.41	303.4	4.4346×10^{-4}	2.48×10^{8}	1.18×10^{9}
337	304.8	6.26	304.2	1.1742×10^{-4}	2.48×10^{8}	1.19×10^{9}
338	305.7	6.12	305.0	0.3611×10^{-4}	2.49×10^{8}	1.19×10^{9}
339	306.6	5.99	305.7	0.1285×10^{-4}	2.50×10^{8}	1.19×10^{9}
340	307.5	5.87	306.3	0.5239×10^{-5}	2.51×10^{8}	1.20×10^{9}

3. Cumulative Energy Density in the Liquid at the Boiling Explosion

For simplicity, the temperature distribution that is the distribution of energy added to the liquid at any instance of time can be presented in terms non-dimensional temperature (θ) and modified Fourier number (η) for various boundary conditions ($x = 0$) as follows:

Case 1: For linearly increasing temperature boundary condition ($T = bt$):

$$T(x,t) = T_0 + 4bti^2 erfc(x/\sqrt{4at}) \tag{1}$$

$$\theta = \frac{T(x,t)-T_0}{bt} = 4i^2 erfc(\eta) \tag{1.a}$$

Case 2: For constant heat flux boundary condition ($q_w = q$):

$$T(x,t) = T_0 + \frac{q_w\sqrt{\alpha t}}{\lambda} erfc(x/\sqrt{4at}) \tag{2}$$

$$\theta = \frac{T(x,t)-T_0}{q_w\sqrt{\alpha t}/\lambda} = 2ierfc(\eta) \tag{2.a}$$

Case 3: For constant temperature boundary condition ($T = T_i$):

$$T(x,t) = T_0 + (T_i - T_0)erfc(x/\sqrt{4at});\quad T_i = (\beta T_b + T_0)/(1+\beta) \tag{3}$$

$$\theta = \frac{T(x,t)-T_0}{T_i - T_0} = erfc(\eta) \tag{3.a}$$

The modified Fourier number (η) in Eqs. (1.a)– (3.a) is defined as: $\eta = \dfrac{x}{\sqrt{4\alpha t}}$ (4)

To have a better image of accumulated energy distribution inside the liquid during heat process, the percentage of cumulative energy $E(\eta)$ residing within the range 0-η to the total energy deposited $E(\infty)$ in the liquid (0-∞) at any instant of time as defined below:

$$\%\,of\ total\ accumulated\ energy = \frac{E(\eta)}{E(\infty)}\times 100\% = \frac{\int_0^\eta \theta(\eta)d\eta}{\int_0^\infty \theta(\eta)d\eta}\times 100\% \tag{5}$$

The average cumulative energy density (energy per unit liquid volume) for any value of η can be given as:

$$\dot{E}(\eta) = \frac{E(\eta)}{\eta} = \frac{\int_0^\eta \theta(\eta)d\eta}{\eta} \tag{6}$$

Considering the cumulative energy density corresponding to the thermal penetration depth (δ_{th}) as the reference one, the relative energy density factor for any value of η can be given as:

$$m = \frac{\dot{E}(\eta)}{\dot{E}(\delta_{th})} = \frac{E/\eta}{E/\delta_{th}} \tag{7}$$

Therefore, the accumulated energy density in the liquid corresponding to the homogeneous boiling scale η^* (t^*, x_e) can be readily obtained from the energy density prior to the boiling explosion on the basis of the penetration depth (δ^*_{th}) once the relative energy density factor, m, corresponding to the homogeneous boiling explosion (t^*, x_e) is known. Following the analytical solution of 1D heat conduction [7] total energy through the liquid boundary prior to the boiling explosion can be obtained as:

$$E^* = \int_0^{t^*} q_w(t)dt \tag{8}$$

For linearly increasing temperature boundary condition: $q_w(t) = \dfrac{2\lambda b\sqrt{t}}{\sqrt{\pi\alpha}};\ \delta^*_{th} = 2.4\sqrt{4\alpha t^*}$ (9.a)

For constant heat flux boundary condition: $q_w(t) = q_w;\ \delta^*_{th} = 2.6\sqrt{4\alpha t^*}$ (9.b)

For constant temperature boundary condition: $q_w(t) = \dfrac{\lambda(T_i - T_0)}{\sqrt{\pi\alpha t}};\ \delta^*_{th} = 2.7\sqrt{4\alpha t^*}$ (9.c)

4. Results and Discussion

Figure 1 depicts the non-dimensional liquid temperature field (θ) for various boundary conditions while Fig. 2 shows spectrum of deposited energy against η at any instance of time. From Figs. 1 and 2 as well as following [7] the instantaneous thermal penetration depth (δ_{th}) can be approximated by η = 2.4, 2.6 and 2.7 for liquid heating with linearly increasing boundary temperature, high boundary heat flux and a constant boundary temperature respectively From Fig. 2, it is quite evident that almost 100% of the total energy is accumulated with in the respective thermal penetration depth (δ_{th}) for all liquid heating cases under consideration. Fig. 3 illustrates the distribution of relative energy density factor, m, with η for various liquid heating conditions. For small values of η, that essentially characterize the homogeneous boiling explosion conditions (x_e, t^*), m is several times higher than unity for any of the liquid heating cases as shown in Fig. 4. The variation of the cumulative energy density in the liquid over η^* as denoted by $\dot{E}^*(\eta^*)$ are tabulated in Table 1, 2, 3 for various liquid heating condition. For a given liquid initial condition, the cumulative energy density in the liquid over a characteristic homogeneous boiling time and space scale, η^* is almost constant irrespective of heating parameter and boundary condition as it should be. However, liquid initial temperature has strong effect on $\dot{E}^*(\eta^*)$ as depicted in Figs. 5 and 6. This is due to the fact that the ability of the liquid to accumulate external energy prior to homogeneous boiling depends on its initial temperature.

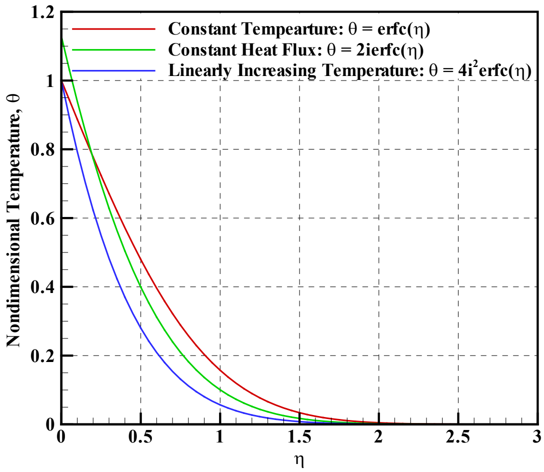

Fig. 1: Spatial temperature distribution for constant heat flux boundary condition

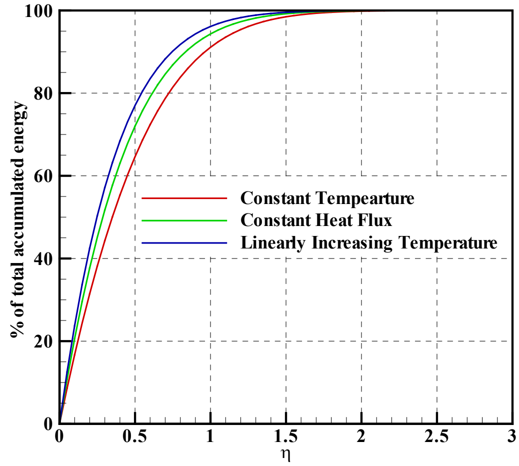

Fig. 2: Spatial distribution of % of total accumulated energy for constant heat flux boundary condition

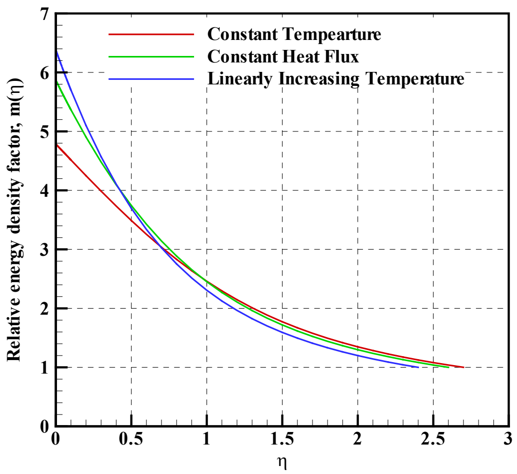

Fig. 3: Spatial distribution of relative energy density factor for constant heat flux boundary condition

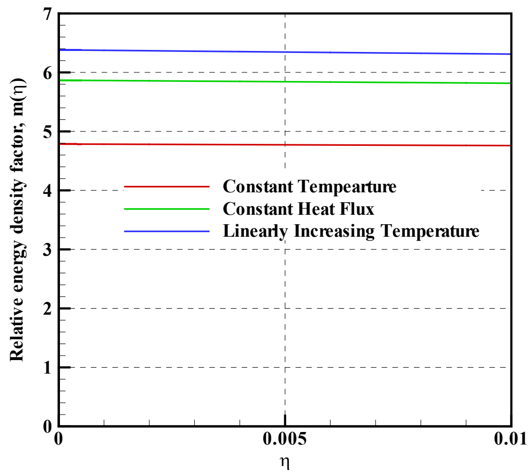

Fig. 4: Cumulative energy density in the liquid at the boiling explosion for constant heat flux boundary condition

Incidentally, the results obtained in this study might be compared with that of [8] for water heating at atmospheric by uniform volumetric heating. For an initial liquid temperature of 100 °C, the cumulative energy density corresponds to a value of about 8.95×10^8 J/m^3 in the present study while that in [8] corresponds to about 8.46×10^8 J/m^3 for homogeneous boiling at a microsecond time scale.

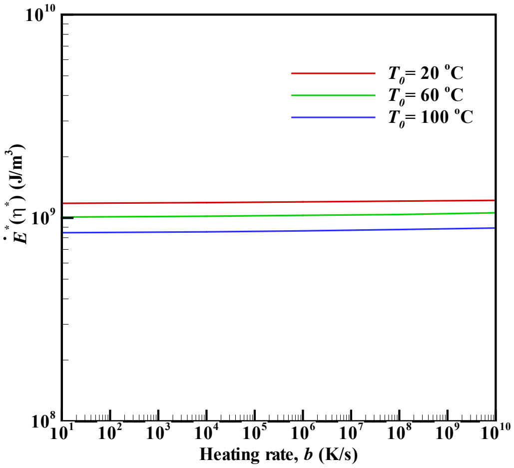

Fig. 5: Effect of liquid initial temperature on the cumulative energy density at the boiling explosion for linearly increasing boundary temperature condition

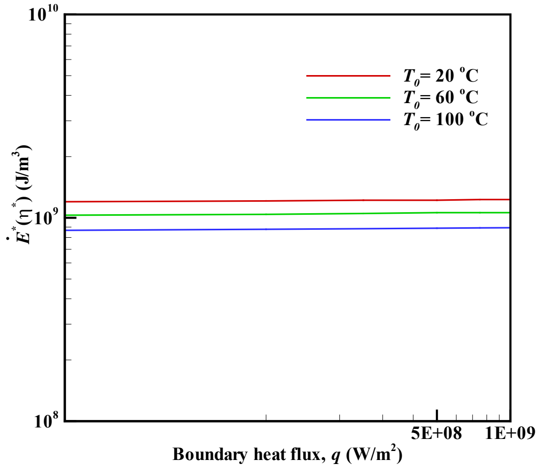

Fig. 6: Effect of liquid initial temperature on the cumulative energy density at the boiling explosion for high heat flux boundary condition

5. Conclusion

The present study elucidates the homogeneous boiling explosion condition from an energy point of view. For a given liquid initial condition, the energy density at the boiling explosion over the characteristics space scale of boiling explosion has been found to be independent of heating parameter in any liquid heating condition. This energy density at the boiling explosion has been found to depend on the liquid initial temperature. The requirement of constant energy density at the boiling explosion for a given liquid initial condition might helpful towards understanding the physics of boiling explosion phenomena in molecular scale when sufficient number of liquid molecules might be super-activated by external energy deposition to initiate the phase change process.

Acknowledgenent

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